

## MICHAEL FARADAY AS A PHYSICAL CHEMIST

SIR HAROLD HARTLEY, F.R.S.

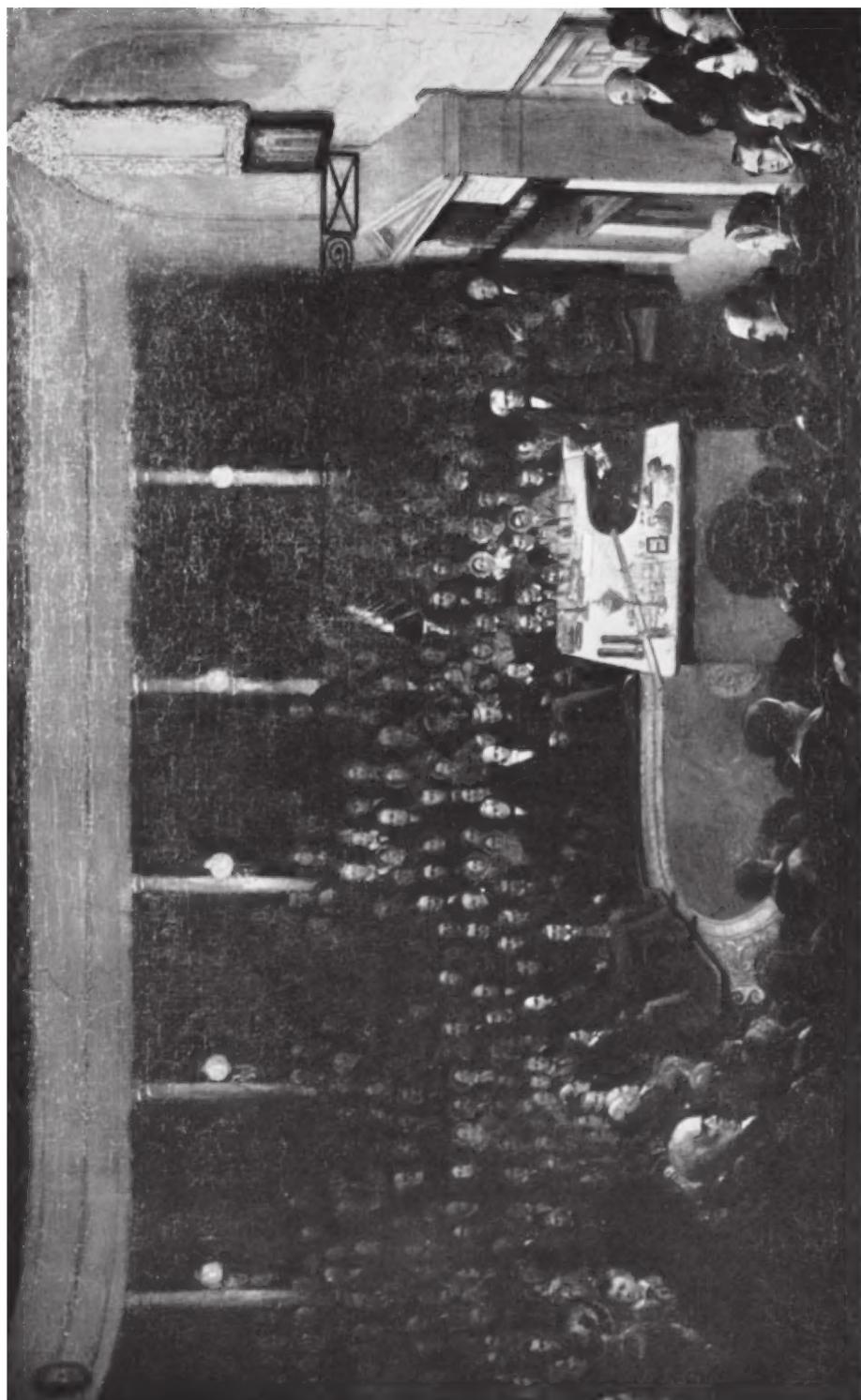
IN speaking of Faraday in this place and on this occasion my thoughts inevitably go back to the young bookbinder's apprentice sitting in the gallery of the old Lecture Theatre over the clock taking those careful accurate notes of the last four lectures which Davy delivered here. Having read them, how Davy must have welcomed the opportunity, two months later, when Mr. Payne, the laboratory assistant had assaulted Mr. Newman, the instrument maker, of recommending Faraday for the vacant post. For twelve years Faraday helped Davy in his researches and he was always grateful for that experience. It was a happy chance that brought together two men with such genius for experiment.

At the start Davy is working on nitrogen chloride and fluoric acid and in October 1813 Faraday went with him on his first long foreign tour. In Paris he is helping in the work on iodine, in Florence with the combustion of the diamond and in Rome with the discovery of iodine pentoxide. Back at the Royal Institution, in October 1815, he is sharing in that brilliant fortnight's work that resulted in the Safety Lamp, and making a fair copy of the paper for the Royal Society. Then Davy starts him on his first independent investigation and there soon followed a steady flow of papers characterized by their factual accuracy and the careful avoidance of any theoretical commitments. They range over a wide field without any consistent theme, recording the results of Faraday's investigations of any new substance or phenomenon he encountered. On the Escape of Gases through Capillary Tubes (1817); On the Solution of Silver in Ammonia (1818); On two new Compounds of Chlorine and Hydrogen (1820), in which he isolates hexachlorethane and tetrachlorethylene; On the Condensation of Several Gases into Liquids (1823); On new Compounds of Carbon and Hydrogen (1825), recording the discovery of benzene and butylene; On the Mutual Action of Sulphuric Acid and Naphthalene (1826), in which he separates the barium salts of  $\alpha$ - and  $\beta$ -naphthalene sulphonic acids.

Meanwhile he was adding to the experience he had gained from Davy his own patient detailed study of laboratory operations, which

Professor Michael Faraday lecturing to the Royal Society  
in the presence of the Prince Consort and the young  
princes, 27th December, 1855.

*Contemporary painting by Alexander Blakeley. Purchased  
from the private collection of the Nowell Faringdon family of  
Worden Hall, Leyland, Lancs., and now owned by the  
Faraday Society.*



FARADAY LECTURING AT THE ROYAL INSTITUTION, 1885—PAINTING BY ALEXANDER BLAKELEY

#### SIR HAROLD HARTLEY

gave his book on "Chemical Manipulation" its unique character. Faraday quickly became a skilful analyst and in these years he was building up a lucrative business as a consultant, earning at the peak over £1,000 a year in this way. His papers with Stodart, a maker of surgical instruments, on steel alloys are typical of his practical outlook, as the work is directed solely to the discovery of steels resistant to corrosion with superior cutting powers. Faraday would sometimes give his friends a razor blade made with his alloy steel. The investigation ceased with Stodart's death in 1822. Later in 1825, when Faraday's help was enlisted in the research sponsored by the Royal Society and the Board of Longitude to improve the quality of British optical glass, furnaces to his design were built at the Royal Institution and he interested himself in all the practical details of glass making. The only positive result of the work was the heavy lead borosilicate glass with which twenty years later he discovered the magnetic rotation of polarized light. It was Faraday's skill in applying scientific methods to practical use that made his services so much in demand by government departments throughout his life.

Faraday's outlook in this early work is shown so well by the final sentence in his paper on naphthalene sulphonic acid. He suggests for this the name "sulpho-naphthalic acid, which sufficiently indicates its source and nature without the inconvenience of involving theoretical views".

He followed Davy and Wollaston in their doubts about the atomic theory and consequently he had no coherent theory of the relation of different chemical substance to one another. He made no attempt to grapple with the problem of their constitution which was just beginning to excite the curiosity of chemists. The truth is that Faraday in spite of his many contributions to chemistry was by nature a physicist. During those years from 1816 to 1830 when his papers were entirely practical, eschewing theoretical inferences, his inner mind was brooding over his early conviction of the essential unity of nature, intent on finding the underlying relation of light, electricity and magnetism. But thanks to his early training with Davy, his wide acquaintance with the properties of many substances, and his unrivalled knowledge of chemical technique, there was always a chemist's background to his experiments which gave them wide scope. It was his dual outlook that made him a key figure in the early history of physical chemistry.

The year 1831 was the turning-point in Faraday's career. There is no greater contrast in scientific literature than his earlier chemical

## MICHAEL FARADAY AS A PHYSICAL CHEMIST

and physical papers characterized by their essentially practical outlook and accomplishment, and the brilliant flights of imagination that inspired his "Experimental Researches in Electricity".

I am convinced that it was the success of an experiment which Faraday had previously tried again and again, without success, that gave the new impulse to his work and gave him confidence in the promptings of his imagination.

Electricity was one of Faraday's earliest scientific interests. Long before he went to Davy he was experimenting with home-made batteries. In his first lecture to the City Philosophical Society in 1816 we get a glimpse of his intuitive belief in the essential unity of the forces of nature. "That the attraction of aggregation and chemical affinity is actually the same as the attraction of gravitation and electrical attraction I will not positively affirm, but I believe they are." In 1821, Faraday repeated the experiments of Oersted, Arago, and Ampère on electro-magnetism and discovered the rotation of a wire carrying a current if free to move round a magnetic pole. Magnetism had been produced from electricity, and Faraday was convinced of the possibility of obtaining electricity from magnetism. In 1824 and again in 1825 and 1828 he was experimenting with a magnet in a wire helix connected with a galvanometer, without result. Either the galvanometer was too insensitive or he failed to detect the momentary deflection when the magnet was introduced. On 29th August 1831, the induced current was detected—Faraday's dream had come true—and ten days of decisive experiment ended in his paper on "The Induction of Electric Currents" which was to shape the future of electrical science and electrical industry.

It is significant of Faraday's train of thought as a pioneer of physical chemistry that the first experiment he made on 29th August 1831, after discovering the induced current, was to attach platinum wires to the ends of the coil and see if he could detect any decomposition of a drop of copper sulphate solution. The test was not delicate enough, and he did not succeed in detecting the chemical power of magneto-electricity until several years later. However, he made a number of experiments on chemical means of detecting the current from a voltaic cell, and on 11th June 1832, he found in bibulous paper moistened with potassium iodide and starch the most sensitive detector.

His discovery of electro-magnetic induction raised afresh in Faraday's mind the old and still disputed problem of the identity of electricities from different sources, and chemical action was one of the tests he applied

to its solution. Having shown that common (frictional), voltaic and magneto-electricity all produce similar physiological, magnetic, chemical and thermal effects, Faraday sought to establish their identity by quantitative experiments. Among the discoveries that Cavendish had made almost fifty years previously, was that the behaviour of an electric charge depends on two factors, the degree of electrification (or potential as we should call it) and the size of the charge. His paper on the torpedo, published in 1776, contains an account of experiments with Leyden jars which demonstrate very clearly this distinction. Faraday had read Cavendish's paper and realized that his theory explained the apparent differences in behaviour of frictional and voltaic electricity. He says : "The beautiful explication of these variations afforded by Cavendish's theory of quantity and intensity requires no support at present, as it is not supposed to be doubted." The theory was, however, by no means generally accepted in 1832, but Faraday's recognition of its truth was the key to the success of his researches on electro-chemistry.

He started out to prove that the effect on a galvanometer of a discharge of frictional electricity was dependent on its quantity and not on its intensity, which he showed on 14th September 1832, by charging 8 Leyden jars in a battery of 15 by means of 30 turns of a frictional machine, and seeing that when discharged through the galvanometer they caused the same throw of the needle as the whole 15 jars charged by means of 30 turns, although an electrometer indicated that the intensity of the charge was roughly one-half in the second case. "Hence", said Faraday, "it would seem that if the same absolute quantity of electricity passed through the instrument whatever may be its intensity, the deflecting force is the same."

He then made a small "standard elementary battery" consisting of platinum and zinc wires  $\frac{5}{8}$ th inch in diameter,  $\frac{5}{16}$ th of an inch apart, which he immersed to a depth of  $\frac{1}{8}$ th inch in dilute sulphuric acid (one drop of acid in 4 oz. water) and he found that by immersing the wires for 8 beats of his watch (3.2 sec) when they were joined to a galvanometer, the momentary deflection of the needle (its half period of swing was 6.8 sec) was the same as that caused by 30 turns of the machine. Hence, said Faraday, the amount of electricity produced by the cell in this time was the same as that produced by 30 turns of the machine. He next compared the amounts of chemical change by allowing the electricity to pass in both cases through filter paper moistened with potassium iodide on a platinum spatula with a platinum

## MICHAEL FARADAY AS A PHYSICAL CHEMIST

wire  $\frac{1}{12}$ th inch in diameter as the positive pole. A brown circle of iodine was found at the point of contact and its tint depended on the number of turns of the machine. Faraday showed by varying the number of turns of the machine that it required approximately 30 turns to produce an iodine spot of the same tint as that given by immersing his standard battery for 8 beats of his watch. "Hence it would appear that both in magnetic deflection and in chemical effect the current of the standard voltaic battery for 8 beats of the watch was equal to the electricity of 30 turns of the machine, and that therefore common and voltaic electricity are alike in all respects." These experiments on 14th and 15th September 1832, were the first attempt to connect the quantity of electricity passing in an electrical circuit with the amount of chemical decomposition.

Faraday was now convinced, it is true on rather slender evidence, that the amount of electro-chemical decomposition is a measure of the quantity of electricity, and his paper on "The Identities of Electricities" contains the first statement of his First Law of Electrolysis: "It also follows that for this case of electro-chemical decomposition and it is probable for all cases, that the chemical power, like the magnetic force, is in direct proportion to the absolute quantity of electricity which passes."

In trying to find the most delicate test for the passage of electricity, Faraday made many new experiments on the chemical action produced by a current. In one of them he placed one end of a long piece of litmus paper moistened with sodium sulphate in contact with an electrical machine, while the other end was held opposite to the discharging points. On turning the machine Faraday saw that decomposition took place, the paper becoming red "where the positive electricity entered from the air". This proved to him that the decomposition was not dependent on the presence of metallic poles in the solution, and on 6th September he wrote in his note-book: "Hence it would seem that it is not a mere repulsion of the alkali and attraction of the acid by the positive pole, etc., but that as the current of electricity passes whether by metallic poles or not the elementary particles arrange themselves and that the alkali goes as far as it can with the current in one direction and the acid in the other. The metallic poles used appear to be mere terminations of the decomposable substance.

"The effects of decomposition would seem rather to depend upon a relief of the chemical affinity in one direction and an exaltation of it on the other rather than to direct attraction and repulsion of the poles."

SIR HAROLD HARTLEY

Faraday's view of the nature of electrolysis had been foreshadowed by Davy in his Bakerian Lecture of 1806 and I feel certain that in his electro-chemical researches, consciously or unconsciously, Faraday owed much to Davy's flashes of inspiration. In his papers scattered over the years 1801 to 1826 Davy had touched on many aspects of the researches that were to occupy Faraday during the next eighteen months. And Faraday's skill in measurement, his patience and his unerring intuition were to give precision and finality to Davy's tentative ideas.

The three main problems he now attacked were :

1. The mechanism of conduction in solution and the dependence of the passage of the current on chemical decomposition.
2. The amount of chemical action accompanying the passage of the current.
3. The source and the intensity of the current produced by voltaic cells.

On 24th December 1832, Faraday wrote in his note-book : "Can an electric current, voltaic or not, decompose a solid body, ice, etc., etc. ? If it can does it give structure at the time ? If it cannot what would fused gum, lac, wax, etc. ?" A cold spell at the end of January enabled him to put this to the test, and he found that while ice would not conduct a voltaic current, conduction occurred immediately the ice melted. "If ice will not conduct is it because it cannot decompose ?"

It was characteristic of Faraday's thoroughness that he went on to examine the conductivity in the fused state of a number of substances which are solid at ordinary temperatures and to study the products formed during electrolysis. It was a new field for him and he showed his usual experimental skill in devising simple methods for working at high temperatures, including even the use of the oxy-hydrogen blowpipe. During February and April he examined over 130 substances and found that while a number resembled water in being insulators in the solid state and becoming good conductors if fused, when they were decomposed by the current, certain of them, such as boric acid, did not conduct when fused. He thus arrived at no general conclusion, but the experience he gained in working with fused salts was to prove invaluable later in the year in his work on electro-chemical equivalents. The experiments were finished on 22nd April, and on 24th April they were communicated to the Royal Society with the title "On a New Law of Electric Conduction".

## MICHAEL FARADAY AS A PHYSICAL CHEMIST

Faraday then turned his attention to the mechanism of conduction in a solution. On 2nd May he passes a strong current through a saturated solution of sodium sulphate and examines it with polarized light both across and along the direction of the current to see if he can detect signs of arrangement of the molecules, but without result. On 20th May he determines the transfer of sulphuric acid during electrolysis by measuring the changes in concentration in two vessels connected by moist asbestos, and on 27th May he shows that the transfer of sulphuric acid differs from that of sodium sulphate of equivalent concentration, "very evident therefore that the transfer is dependent on the mutual action of the particles". He summed up his views in a paper to the Royal Society on 18th June, the main conclusion being "that electro-chemical decomposition does not depend on the simultaneous action of two metallic poles", and the effects of it "are due to a modification, by the electric current, of the chemical affinity of the particles through or by which that current is passing, giving them the power of acting more forcibly in one direction than in another, and consequently making them travel by a series of successive decompositions and recompositions in opposite directions, and finally causing their expulsion or exclusion at the boundaries of the body under decomposition".

In May 1833 Faraday's thoughts were returning to the question of the amount of chemical action that takes place during the passage of a current. On 16th May no experiments were recorded in the note-book, but among the ideas he jotted down was : "Is the law this (above a certain intensity, i.e. the one required for decomposition to take place at all), that whatever the size of plates, or number intervening, or constant section of decomposing matter, or variable section, or variable strength, or number of series in the battery : that . . . equal currents of electricity measured by the galvanometer evolve equal volumes of gas or effect equal chemical action in a constant medium ?" A week later he writes down his plans for testing the law : "By putting cups and expts. in succession and sending the same electrical current through both or all am sure that each is submitted to an equal force. Can try well this way whether the same quantity of different intensity does the same chemical work using same dilute sulphuric acid but *different-sized poles*, and collecting gas, and that will tell—some poles mere wires, others large plates." Three months elapsed before he actually carried out the experiment. On 27th August he wrote : "Pursue the investigation, whether

#### SIR HAROLD HARTLEY

the same quantity of electricity *always* produces an equivalent of chemical decomposition. . . ." On 31st August he found, as he expected, that the same amount of current liberated the same volume of gas irrespective of the concentration of the acid, the size of the electrodes, or the intensity of the current. He obtained the same results with solutions of various salts, and his comment was : " Strange that with such different substances the same quantity of water should be decomposed by the same current." These experiments were continued in September, and Faraday was constantly puzzling over the effect of various substances in increasing the conducting power of water. On 17th September he showed that cells containing muriatic and sulphuric acids had given the same volume of hydrogen when connected in series, and he was now busy constructing a simple apparatus to measure the quantity of electricity by means of the volume of gas produced by it. " The instrument offers the only actual measurer of voltaic electricity which we at present possess. . . I have therefore named it a volta-electrometer." (The name was contracted to voltameter five years later.) Today, following Faraday, we define our practical unit of current by its electrolytic action, and we use his name to denote the fundamental unit of electro-chemistry.

On 19th September, among his observations, he notes " Will not white-hot diamond conduct ? If so may perhaps crystallise carbon at white heat by power of the voltaic battery."

He had been worried by the contraction, on standing, of the mixture of oxygen and hydrogen obtained in the electrolysis of sulphuric acid. He traced this to the catalytic activity of the platinum electrode, and showed that the positive and not the negative was effective. This observation led him to spend some weeks investigating the conditions under which platinum and other metals would assist the combination of various gases, when he discovered the retarding effects caused by small quantities of gases such as olefiant gas, carbonic oxide, and sulphuretted hydrogen. The results were communicated to the Royal Society on 30th November.

Faraday then returned to the investigation of the amount of chemical action produced by the current, and as he recognized that in the electrolysis of aqueous solutions it was doubtful whether the elements liberated at the poles were to be regarded as primary or secondary products, he extended the inquiry to include fused substances, which would be free from this ambiguity.

Hitherto Faraday had only compared the quantities of the same

### MICHAEL FARADAY AS A PHYSICAL CHEMIST

substances, such as hydrogen liberated by the same current in a series of cells, but he now began to consider the relative quantities of different elements that would be liberated by the same current. On 23rd September he wrote : " Think it will be very important to have a new relation of bodies, under the term *electro-chemical equivalents*, tabulated. Very important as to decomposing powers of the pile, as to the true expression of equivalent numbers, and as to nature of chemical affinity and its relation to electrical states and powers."

In the last paper Davy read to the Royal Society in 1826 there is a notable passage in which he foreshadowed Faraday's classic investigation. " In the Bakerian Lectures of 1806 I proposed the electrical powers, or the forces required to disunite the elements of bodies, as a test or measure of the intensity of chemical union. By the use of the multiplier, it would now be easy to apply this test ; and accurate researches on the connexion of what may be called the electro-dynamic relation of bodies to their combining masses or proportional numbers, will be the first step towards fixing chemistry on the permanent foundations of the mathematical sciences."

On 28th September in discussing the results of experiments in which a current is passed through a sulphuric acid voltameter, and various solutions in series with it, Faraday decided that in aqueous solution the current is probably carried by hydrogen and oxygen, these being always the primary products of electrolysis. " When, therefore, metallic solutions are decomposed the metals are evolved not by the current of electricity but by the hydrogen evolved at the N. Pole. . . . Hence it will probably follow that in these cases the metal is an equivalent of the hydrogen because it is produced chemically by the hydrogen, and therefore such effects *will not PROVE* the equivalent character of the products of true electro-chemical decomposition. . . . Perhaps fused nitre will be a good salt to compare by current with decomposition of water. Or fused chloride of lead or tin." These experiments with fused salts, which removed any doubt as to whether the elements liberated during electrolysis were primary or secondary products, were not carried out until December, but doubtless in the interval Faraday was making plans for them.

On 17th December he wrote in his note-book : " Proceeded to decompose dry chlorides, oxides, etc., to ascertain if there also the decomposition was definite and what the equivalent numbers would be." So quickly was the final stage in the investigation



MICHAEL FARADAY

*National Portrait Gallery*

[To face page 482]

SIR HAROLD HARTLEY

accomplished that on 9th January 1834, the paper containing the Laws of Electrolysis was communicated to the Royal Society. In the first experiment on 17th December fused stannous chloride in a glass tube was decomposed with platinum wire poles with a voltmeter in series, and the weight of the tin liberated compared with the weight of water (0.26486 grain) decomposed in the voltmeter. "1.76 of tin had been electro-chemically evolved at the exode, and of course a corresponding portion of chlorine at the cisode. Now

$w \quad t$

0.26486 : 1.76 : : 9 : 59.805 the tin.

"The number for tin is given 58 which is very near indeed for a first experiment, and shows that the electro-chemical equivalent is the same as the chemical equivalent here." Note Faraday's first efforts at a new terminology, "exode" and "cisode". Later on the same day the word "pole" which suggests the idea of attraction or repulsion, was struck out and "electrode" written above it for the first time.

On the following day another experiment with stannous chloride gave a value of 53.833 for tin. Two similar experiments with fused lead chloride gave electro-chemical equivalents for lead of 105.11 and 97.22, the chemical equivalent being 103.5 or 104. Faraday wrote of the lower value: "Hence it is too little, but still so near as to establish the principle of electrochem equivalents."

On 19th December no experiments are recorded, but doubtless Sertg. Anderson was helping Faraday to set up apparatus, and fresh glass vessels with fused-in electrodes had to be blown for each experiment. A few extracts from the note-book on that day show the activity and range of Faraday's mind :—

- 1192. "With regard to *INTENSITY* and its meaning, etc., Define intensity if possible and state its relation to *quantity, time and conducting power.*"
- 1195-1200. "Nervous agency of Electricity."
- 1207. "In the table I mean Real Electro chemical equivalents not hypothetical for we shall else outrun fact and lose the information directly before us. . . . I must keep my researches really *Experimental* and not let them deserve anywhere the character of *hypothetical imaginations.*"
- 1212. "Search for Fluorine by using plumbago Pos. Pole acting on a fluoride."

## MICHAEL FARADAY AS A PHYSICAL CHEMIST

1213. "This process may finally give rise to some very good processes of analysis in determining weights or at least to some excellent modes of comparing weights of metals . . . *a good principle of analysis* for it will hold probably in salts as well if properly selected and may use mercury electrodes when convenient."

A remarkable anticipation of modern methods of electrolytic analysis.

With the exception of Christmas Day, determinations were made every day. On 26th December Faraday comments in his diary on the enormous quantity of electricity required to decompose a small amount of water. Later he estimates that 800,000 charges of a Leyden battery, each one of which would suffice to kill a cat, "would be necessary to supply electricity sufficient to decompose a single grain of water ; or, if I am right, to equal the quantity of electricity which is naturally associated with that grain of water, endowing them with their mutual chemical affinity !"

The experiments on the electrolysis of fused salts were difficult and often gave inconclusive results, but confirmatory evidence was obtained from lead borate and iodide.

Faraday was anxious to extend the work to the deposition of metals from aqueous solutions, and he found that zinc deposited on a platinum electrode gave an electro-chemical equivalent of 34.08 while the loss in weight of amalgamated zinc in a platinum-zinc cell compared with the weight of hydrogen evolved gave in two experiments equivalents of 30.2 and 32.31. "Excellent", he writes after the latter result, to which he attached great importance, as it was the first occasion on which he had compared the amount of chemical action in a voltaic cell with that produced by the current in the external circuit. This confirmed his conviction "that the quantity of electricity which, being naturally associated with the particles of matter, gives them their combining power, is able, when thrown into a current, to separate those particles from their state of combination ; or, in other words, that the electricity which decomposes, and that which is evolved by the decomposition of a certain amount of matter, are alike.

"The harmony which this theory of the definite evolution and the equivalent definite action of electricity introduces into the associated theories of definite proportions and electro-chemical affinity is very great. According to it, the equivalent weights of bodies are

simply those quantities of them which contain equal quantities of electricity . . . it being the ELECTRICITY which determines the equivalent number, because it determines the combining force. Or if we adopt the atomic theory or phraseology then the atoms of bodies . . . have equal quantities of electricity naturally associated with them. But I must confess I am jealous of the term atom, for though it is very easy to talk of atoms, it is very difficult to form a clear idea of their nature."

These sentences must have been written immediately after the experiments were made, as the paper was communicated to the Royal Society on 9th January. This paper is the most important of Faraday's contributions to electro-chemistry, and in it he summarizes all his previous work. He begins by introducing the new terminology which he devised with the help of Whewell for the sake of greater precision of expression, and all his new names—electrode, anode, cathode, ion, anion, and cation, electrolyte and electrolysis—we use today with the significance which Faraday gave to them. After a short account of the conditions necessary for electro-chemical decomposition, he describes his new volta-electrometer and the evidence that led him to the conclusion that the amount of chemical action is dependent solely on the amount of electricity that passes through it. He next discusses whether the products of electrolysis are primary or secondary, and gives his evidence for the identity of chemical and electro-chemical equivalents.

The researches had strengthened enormously the evidence for his First Law of Electrolysis—"The Chemical power of a current of electricity is in direct proportion to the absolute quantity of electricity which passes"; and they had established the Second Law—"Electro-chemical equivalents coincide and are the same with ordinary chemical equivalents." The exactness of these two laws has been confirmed by every subsequent investigation.

Faraday then spent a month carrying out a large number of experiments on the intensity required to produce electrolysis of different solutions by varying the number of cells in the battery and seeing how many were required to electrolyse various compounds in solution or in a fused state. One of his difficulties was that he had no unit to measure by, and on 10th February he notes, "The power of decomposing water a good *unit* of intensity in voltaic apparatus".

The general result of these experiments was to strengthen Faraday's conviction that the source of the current was the chemical reaction

### MICHAEL FARADAY AS A PHYSICAL CHEMIST

taking place in the voltaic cell and not the mere contact of two metals, and indeed he proved that a current is produced without such contact by interposing a slip of paper moistened with potassium iodide solution between the metals. His thoughts were concentrated on the relation between chemical action and the production of electricity, and he realized that whether a current passes or not depends on the relative magnitudes of the chemical affinities of the reactions taking place in the battery and in the electrolytic cells. In discussing this problem on 12th February he writes: "The whole arrangement seems beautifully to show that antagonism of the *chemical powers* and the Electromotive parts with the *chemical powers* and the interposed parts. The first are producing electric effects, the second opposing electric effects, and the two seem equipoised as in a balance, and in both cause and effect appear to be identical with each other. Hence chemical action merely electrical action and Electric action merely chemical." Again on 19th February: "Affinity is action at both points, but is as it were connected or related by the current of electricity in the communicating wires, or in other words affinity is electricity and vice versa."

Three days later he wrote: "We seem to have the power of deciding in certain cases of chemical affinity (as of zinc with the oxygen of water) which of two modes of action of the *one power* shall be exerted. In the one mode we can transfer the power on, it being able to produce elsewhere its equivalent of action; in the other it is not transferred on but exerted at the spot. The first is the case of Voltaic Electric production, the other the ordinary cases of chemical affinity. But both are chemical actions and due to one power or principle."

In other words, Faraday saw that a chemical reaction can be carried out in two ways, either by means of a voltaic cell in which the reactants are separated by an electrolyte, or by their direct contact, and further, he identified the electro-motive force of the cell with the chemical affinity of the reaction. Half a century was to elapse before the conception of chemical affinity assumed a definite form in chemists' minds, but here Faraday anticipates our modern interpretation. His method of reasoning, too, is an instinctive recognition of the Law of Conservation of Energy, and it was in connection with the chemical theory of the cell that he wrote in 1840: "In no case . . . is there a pure creation or production of power without a corresponding exhaustion of something to supply it."

SIR HAROLD HARTLEY

All these results were collected in a paper "On the Electricity of the Voltaic Pile", and communicated to the Royal Society on 7th April. This was really the last of Faraday's great contributions to electro-chemistry, although a few papers of minor importance came later.

Faraday's researches had a most profound and immediate effect on the progress of electro-chemistry. Within two years he changed the whole aspect of the subject and gave it a coherent structure and a quantitative basis, as a result of his laws of electrolysis, his new ideas which were crystallized in his new nomenclature, and his association of the intensity of the voltaic cell with the chemical affinity of the reaction taking place in it.

It is remarkable, too, how many of Faraday's ideas and discoveries had a decisive influence on the development of electro-chemistry in the nineteenth century, and have even today a direct bearing on modern theories. His experiment on the transfer of sulphuric acid during electrolysis inspired the investigation of Daniell, which proved that the current in aqueous solution is carried by the ions of the solute, and not as Faraday supposed by the ions of hydrogen and oxygen. Later its development of Hittorf led to the conception of transport numbers, which has played so important a part in the theory of solutions.

Again in 1834, Faraday pointed out that if "we adopt the atomic theory or phraseology then the atoms of bodies . . . have equal quantities of electricity associated with them". Had he been a believer in the atomic theory he might have made the deduction that electricity, like matter, is atomic in nature. It was left most appropriately to Helmholtz in his Faraday lecture given in this theatre in 1881, to point out this most startling result of Faraday's laws : "If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into elementary portions, which behave like atoms of electricity." Thus Faraday's laws led directly to the conception of the electron.

One further example—Faraday first pointed out the enormous size of the electrical charge carried by each ion. Chemists and physicists lost sight of this fact until Helmholtz recalled their attention to it fifty years later in his Faraday lecture, and showed that the attractive force between the electrical charges associated with hydrogen and oxygen is 71,000 billion times greater than the gravitational

## MICHAEL FARADAY AS A PHYSICAL CHEMIST

attraction between their masses. Again many years passed before first Milner and then Debye and Hückel showed that the magnitude of these interionic forces could account for the so-called anomalies of strong electrolytes. There is thus a direct link between Faraday and the most modern theory of solutions.

After 1834 Faraday's researches were mainly physical but each in turn has had its influence on physical chemistry, an influence that is still felt today. In 1837 came his paper on Induction, dependent on the property of the dielectric medium which he defined as its Specific Inductive Capacity. Faraday thought of the particles of the dielectric as polarized, which finds its modern counterpart in their dipole moments.

In September 1845, at long last, he found the effect of magnetism on light in the rotation of the plane of polarization in a magnetic field, one of his most exciting discoveries. And although as a so-called additive property magnetic rotation did not fulfil its early promise, today it has its value in determining paramagnetic susceptibilities connected with the spin of electrons.

The discovery of diamagnetism in November 1845 led up to his paper on the "Magnetic Condition of all matter". This opened a new line of investigation which today finds many applications in the study of the detailed structure of atoms and molecules.

In 1846 came Faraday's boldest speculation in his paper on "Thoughts on Ray-Vibration," foreshadowing the electro-magnetic theory of light. Clerk Maxwell's mathematical interpretation of Faraday's physical conceptions revealed, as von Helmholtz said, the quite wonderful sincerity and intellectual precision with which Faraday performed in his brain the work of a great mathematician without using a single mathematical formula.

With the marvellous intuition that guided Faraday to the fundamentals of any problem and with his genius for experiment, it is no wonder that physical chemistry in so many fields still bears the impress of his mind. So often Faraday's experiments were not the exploration of an uncharted field, but the verification for himself of his instinctive recognition of Nature's ways. As Kohlrausch said of him "Er riecht die Wahrheit"—he smells the truth; or in Tyndall's words, "Faraday was more than a philosopher; he was a prophet".